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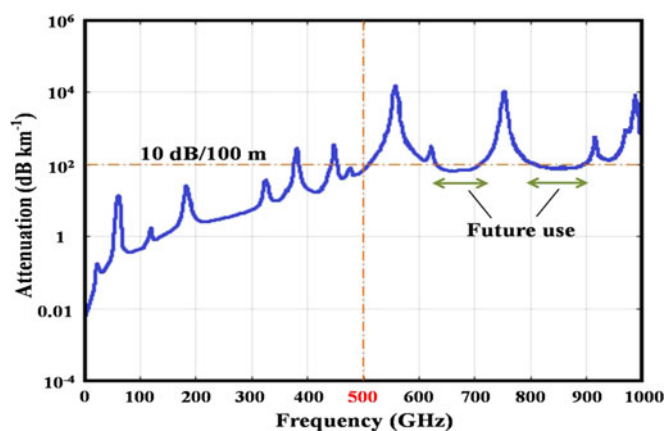
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Abstract: In this paper, a terahertz (THz) wireless communication system at 400 GHz with various modulation formats [on–off keying (OOK), quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), and 32-quadrature amplitude modulation (32-QAM)] is experimentally demonstrated based on photonic generation of highly pure THz carriers. The experimental THz wireless photonic transmission system is enabled by the ultrawideband behavior of an antenna-integrated untraveling-carrier-photodiode-based transmitter and a Schottky mixer-based THz receiver. In the experiment, a phase-correlated optical frequency comb (OFC) is created for photomixing generation of the desired THz carrier frequencies with low phase noise. The OFC allows for the generation of flexibly tunable THz carrier frequencies. The performance of the generated THz carriers is experimentally characterized in terms of phase noise, spectrum purity, tunability, and long-term stability. In the case of generating 400 GHz carrier, the measured timing jitter, linewidth, and long-term stability in the experiment are 51.5 fs, less than 2 Hz, and less than ± 1 Hz with 3 hours, respectively. We also theoretically analyze the phase noise of photonic generated THz beat-notes when phase correlation of two optical comb tones is damaged due to their path-length difference. In addition, we demonstrate THz wireless transmission of various modulation formats, including OOK, QPSK, 16-QAM, and 32-QAM at beyond 10 Gb/s in such a system, and the measured bit error rate (BER) performance for all the signals after 0.5 m free-space delivery is below the hard decision forward error correction threshold of 3.8×10^{-3} . Furthermore, the influence of THz carrier purity on the system performance is experimentally analyzed with respect to the BER of the THz communication signals.

Index Terms: THz wireless communication, THz photonics, untraveling carrier photodiode (UTC-PD), phase noise, optical frequency comb (OFC), photomixing.

1. Introduction

Nowadays, our daily life increasingly depends on on-line services in accordance with both the popularity of the Internet and the outstanding growth of wireless technology [1]–[4]. For instance,

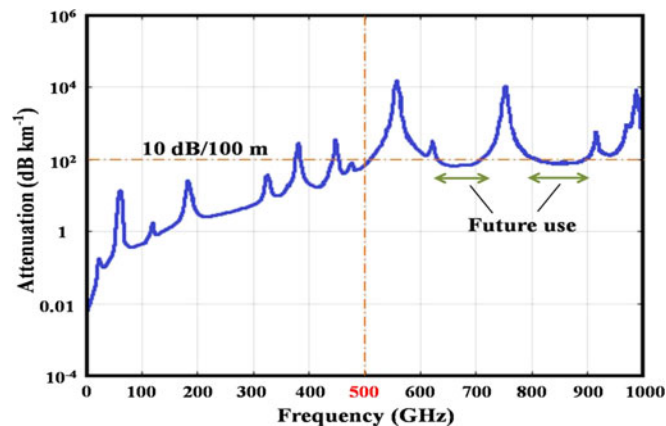


Fig. 1. Atmospheric attenuation of radio waves [19].

in the future, the wireless transmission of Ultra High Definition (UHD) videos will allow us to enjoy highly realistic sensation teleconferences in the office or at home, instead of traveling all over the world [5], [6]. As the radio-frequency (RF) bands up to 60 GHz are almost saturated at present, in the long run, there is no alternative but to move toward higher frequency bands with larger available bandwidth in order to be able to support emerging bandwidth-hungry services [7], [8].

Indeed, the exploration of higher frequency bands for wireless data transmission has attracted a lot of interests in recent years, and several demonstrations operating at beyond 60 GHz have been investigated [9]–[18], for example, hybrid optical fiber-wireless links based on photonic heterodyne up-conversion in the W-band (75–110 GHz) [11], [12]; a dual-channel with amplitude shift keying (ASK) modulation at 140 GHz [13]; a single-input single-output (SISO) wireless communication system at 237.5 GHz [8]; and an 8 Gb/s wireless transmission at 250 GHz [14]. In the terahertz (THz) regions above 300 GHz, 24 Gb/s wireless transmission at 300 GHz [15], a 350 GHz wireless communication system using the current state-of-the-art in THz technology on hardware parameters [16], a giga-bit wireless link in the 300–400 GHz band using photonic generation of high power continuous terahertz-wave signals [17], and a 400 GHz carrier QPSK data wireless transmission system with real-time capable detection [18] have been demonstrated to explore THz frequency bands for communication. From the view point of atmospheric attenuation of electromagnetic waves, 500 GHz is nearly the upper limit in “last-mile” applications, as shown in Fig. 1 [19]. Note that the environmental conditions (RH%, temperature and pressure) are also important to the atmospheric attenuation of electro-magnetic waves; here, we only consider the relatively good environmental conditions in the indoor lab. In addition, wireless transmission systems in the 400–500 GHz band is still in its very early stage.

In this paper, we experimentally demonstrate a THz photonics wireless transmission link at 400 GHz band, with various modulation formats, such as on–off keying (OOK), quadrature phase-shift keying (QPSK), 16 quadrature amplitude modulation (QAM), and 32-QAM. The system is based on coherent photonics for generating highly pure THz carriers. A phase-correlated optical frequency comb (OFC) based on two phase modulators (PMs) in series enables photo-mixing generation of tunable THz carrier frequencies up to 500 GHz. We characterize the performance of photonically generated THz carriers, including phase noise, spectrum purity, linewidth, long-term stability, and tunability. In terms of 400 GHz, the timing jitter calculated from the measured phase noise, linewidth, and long-term stability are 51.5 fs, less than 2 Hz, and less than ± 1 Hz with 3 hours, respectively. In addition, we theoretically analyze the phase noise of photonically generated THz beat-notes. Furthermore, the influence of THz carrier purity on the system performance is experimentally analyzed by measuring the BER of the THz communication signals.

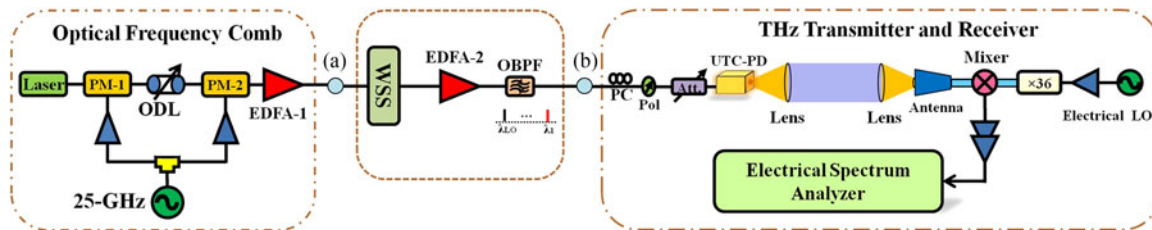


Fig. 2. Experimental setup for coherent generation of THz carriers. PM: phase modulator, ODL: optical delay line, EDFA: erbium-doped fiber amplifier, WSS: wavelength selectable switch, PC: polarization controller, OBPF: optical bandpass filter, LO: local oscillator, Pol: Polarizer, Att.: attenuator, UTC-PD: uni-traveling carrier photodiode.

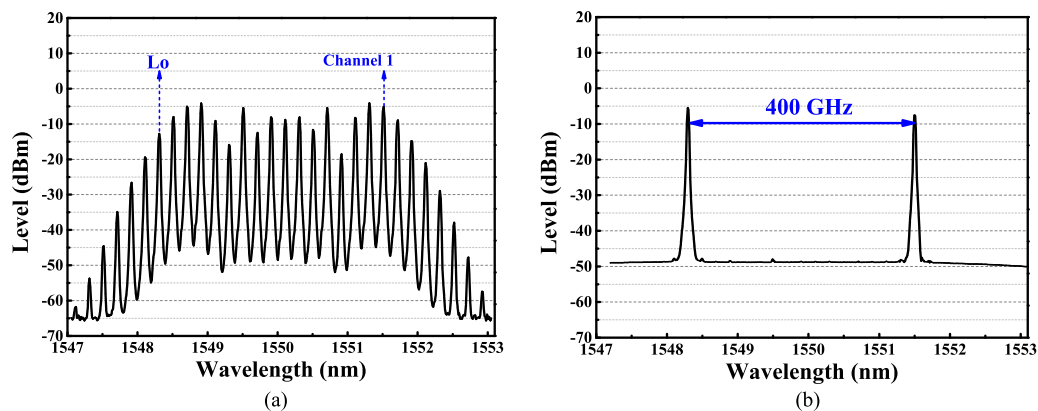


Fig. 3. (a) Spectrum of the generated OFC. (b) Combined spectrum before launched into the UTC-PD.

2. Experimental Generation and Characterization of THz Carriers

2.1. Coherent Generation of THz Carriers

The block diagram of the experimental setup for coherent generation of THz carriers is shown in Fig. 2. In the optical frequency comb (OFC) part, a continuous wave (CW) light from a laser at around 1550 nm is modulated by two cascaded phase modulators (PMs) with a tunable optical delay line (ODL) in between. The two PMs are both driven by an amplified 25-GHz sinusoidal radio frequency (RF) signal from a single synthesizer, which determines the frequency spacing of the OFC. Here, the ODL is optimized to achieve a timing match between the two PMs so that the spectrum of the OFC is broadened for higher frequency THz signal generation, e.g., up to 500 GHz. The spectrum of the generated OFC at point (A) is displayed in Fig. 3(a). Then a wavelength selective switch (WSS) is used to selectively filter two phase-correlated lines from the amplified OFC. The wavelength spacing between these two comb lines is the desired THz carrier frequency, which complies with the operation bandwidth of the THz receiver, which, here, is 325–500 GHz. The two comb tones are then amplified by the EDFA-2 and filtered by a 9 nm optical band pass filter (OBPF) to suppress out-of-band amplified spontaneous emission (ASE). The combined spectrum is shown in Fig. 3(b), with 400 GHz wavelength spacing.

Finally, the two comb lines are photo-mixed in a packaged UTC-PD, which is from Nippon Telegraph and Telephone Electronics in Japan, to generate a 400 GHz carrier. A polarization controller (PC) and a polarizer are employed before the UTC-PD, to align the polarization state. The optical power illuminating the UTC-PD is controlled by a variable optical attenuator (VOA). In the 50 cm free space path, a pair of THz lenses is employed to collimate the THz beam. The received THz carrier is initially down-converted into a microwave intermediate frequency (IF) in the receiver by using a sub-harmonic Schottky mixer operating in the 325–500 GHz band, which is from

Virginia Diodes in the USA. The mixer is driven by a 36-time frequency multiplied electrical local oscillator (LO). Note that in the free space, 400-GHz THz signal is indeed sensitive to polarization misalignment, and hence the antennas at transmitter and receiver should be both polarization-related. In this experiment, the bow-tie antenna integrated in the UTC-PD is Y-polarized, which is the same as that at receiver, and the loss within 50-cm free space is less than 2 dB. Then, the down-converted IF signal is amplified by two cascaded RF amplifiers with a total gain of around 42 dB and measured by an electrical spectrum analyzer (ESA, Anritsu MS2830) for analyzing the performance of the THz carrier.

2.2. Characterization of THz Carrier Performance

In order to characterize the generated THz carriers, the linewidth, tunability, phase noise, and long-term stability are measured by the ESA. The spectrum of the generated 400-GHz THz carrier is investigated by measuring the down-converted IF signal spectrum at reception after wireless delivery, at 5-MHz span and 30-kHz resolution bandwidth (RBW), which is shown in Fig. 4(a). As the limitation of ESA's 1-Hz minimum RBW, its full width at half maximum (FWHM) Δf_{FWHM} is measured as less than 2 Hz at 300 MHz span and 1 Hz RBW, which is inserted in Fig. 4(a). The tunability is enabled by adjusting the WSS to selectively filter two comb lines with different wavelength spacing. By measuring the power of down-converted IF signals corresponding to 325, 350, 375, 400, 425, 450, 475, and 500 GHz, the frequency tunability is shown in Fig. 4(b), where the corresponding spectra are exhibited as well. The stability is of significance to the THz carrier, including two aspects: the instantaneous stability and the long-term stability. The instantaneous stability is evaluated by timing jitter, which can be calculated from measured phase noise of the THz carrier. The measurement is performed by the spectrum analyzer (Anritsu MS2830), and the single-sideband (SSB) power spectral density $L(f)$ of the THz signal is shown in Fig. 4(c), where the offset frequency f ranges from 10 Hz to 10 MHz. The timing jitter could be derived from $L(f)$ [20]

$$\sigma_j = \frac{1}{2\pi f_0} \sqrt{2 \int_{f_{\min}}^{f_{\max}} L(f) df}, \quad (1)$$

where f_0 is the center frequency (400 GHz here), and $[f_{\min}, f_{\max}]$ is the offset frequency range. According to the measurement of $L(f)$, the timing jitter of the THz carrier is 51.5 fs.

The long-term stability can be evaluated by measuring long-term frequency drift of the THz carrier. Here, the THz carrier frequency drift is investigated by measuring that of the down-converted IF signal. When the ESA is set with 300 Hz span and 1 Hz RBW, we test the system for of 3 hours. According to the measurement, the corresponding frequency drift of the THz carrier is less than ± 1 Hz, which indicates that the THz carrier coherently generated by the OFC is with high instantaneous and long-term stabilities.

3. Experimental Investigation of the Influence of Beating Path-Length Difference on Communication System Performance

As shown in Fig. 5, in the block diagram of the experimental setup, the parts of OFC and THz transmitter/receiver are the same as those in Fig. 2. Here, a real-time oscilloscope (RTO, Keysight DSOZ634A Infiniium) is instead used in the receiver for analog-to-digital conversion and communication performance analysis. The sampling rate and bandwidth of the scope are 160 GSamples/s and 63 GHz, respectively. Between points (a) and (b) in Fig. 5, two comb lines spaced by 400 GHz from the WSS are separated into two different output ports. One is used as the optical LO and the other used for optical modulation. These two comb lines are combined and amplified with the EDFA-2 for heterodyne generation of THz signal. Similarly, an OBPF is used to reject out-of-band ASE before launching into the THz transmitter.

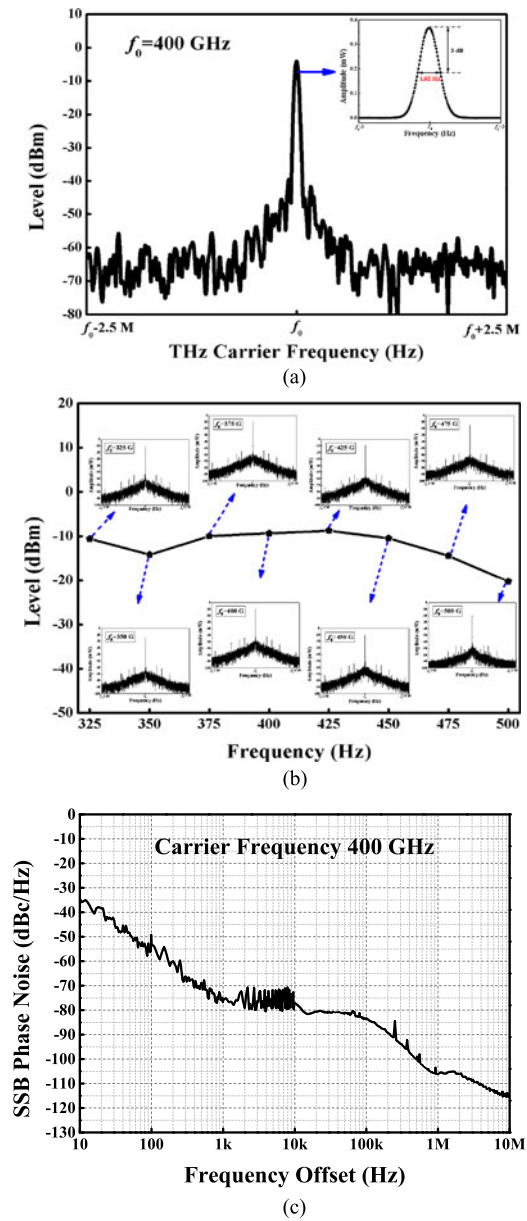


Fig. 4. (a) Electrical spectrum of generated THz carrier at 400 GHz. (b) Tunability of the generated THz carriers. (c) Single sideband (SSB) phase noise of generated 400 GHz carrier.

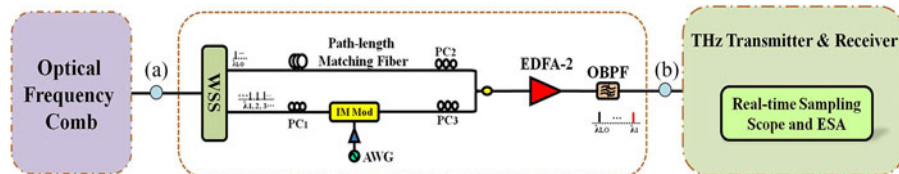


Fig. 5. Experimental setup for investigating the influence of beating path-length difference on the performance of communication system. IM: intensity modulator, AWG: arbitrary waveform generator.

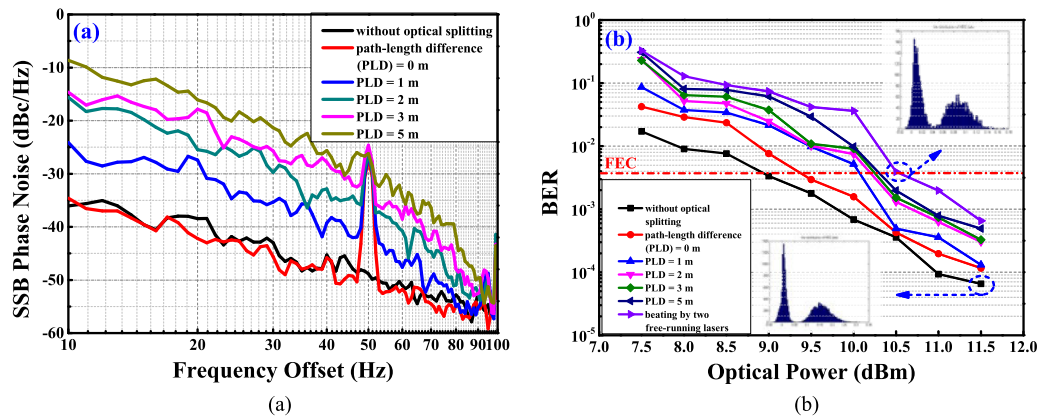


Fig. 6. (a) Phase noise of the generated 400 GHz carrier with different ΔL s. (b) BER performance of OOK modulation at 400 GHz with different ΔL s.

When the baseband data is not applied to the intensity modulator (IM), we investigate the phase noise performance of 400 GHz analogue signal by measuring that of the down-converted IF signal. The length difference between the two optical paths, defined as ΔL , would result in the optical phase de-correlation between the two selected lines and, hence, in principle, causes phase noise degradation of the THz carrier generated by photo-mixing two lines. Therefore, a fiber delay is employed in the optical LO path to compensate the ΔL . The phase noise in different cases is measured, as shown in Fig. 6(a). For comparison purpose, the phase noise by coherent beating two optical lines without splitting (in Fig. 2) is also displayed. It can be seen from Fig. 6(a) that when ΔL is 0 m, meaning the LO path is accurately compensated by a piece of matched fiber, the phase noise performance of THz carrier is almost the same as that in coherent beating. However, the phase noise of 400 GHz signal is becoming worse and worse when 1, 2, 3, and 5 m path-length difference are introduced. In addition, the peak generated on phase noise curve is the beating noise, generated by photo-mixing two lines with phase de-correlation.

In addition, we investigate the influence of path-length difference on communication system performance by modulating a 10 Gb/s OOK baseband data generated from an arbitrary waveform generator (AWG) onto the IM, and analyzing the BER of the received IF signal after a 50 cm free space transmission in the scope. The measured BER results are shown in Fig. 6(b), where two amplitude distribution diagrams corresponding to the BER of 6.5×10^{-5} and 4×10^{-3} after digital demodulation are also exhibited. We can observe that the BER performance in the cases without optical splitting and with the beating of two free-running lasers is the best and worst, respectively. In between the BER gets worse when ΔL increases from 0 to 5 m, which agrees well with the phase noise analysis. Therefore, the path-length difference caused optical phase de-correlation has significant influence on the communication system performance, due to the phase noise degradation of generated THz beat-notes.

4. Experimental Demonstration of 400 GHz QPSK/16-QAM/32-QAM Transmission

The experimental configuration is shown in Fig. 7. Compared to the experimental setup in Fig. 5, the OFC generation and THz transmitter/receiver are the same, while an in-phase (I) and quadrature (Q) optical modulator (I/Q Mod) is employed for implementing multi-dimensional modulation. In order to explore higher-order modulation formats, we perform 5 GBd QPSK/16-QAM/32-QAM and 7.5/10 GBd 32-QAM in the experiment. It is noted that a piece of fiber with an optimized length is used in the optical LO path to match the path length difference between the LO and the modulated line here.

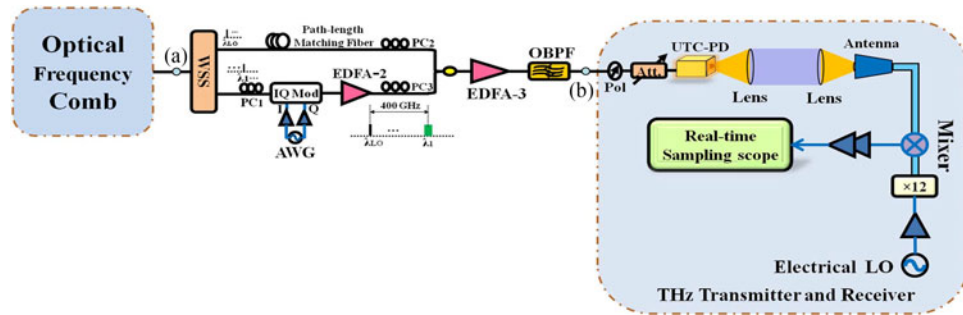


Fig. 7. Experimental setup of 5 GBd QPSK/16-QAM/32-QAM and 7.5/10 GBd 32-QAM data transmission at 400 GHz. IQ Mod: in-phase (I) and quadrature (Q) optical modulator.

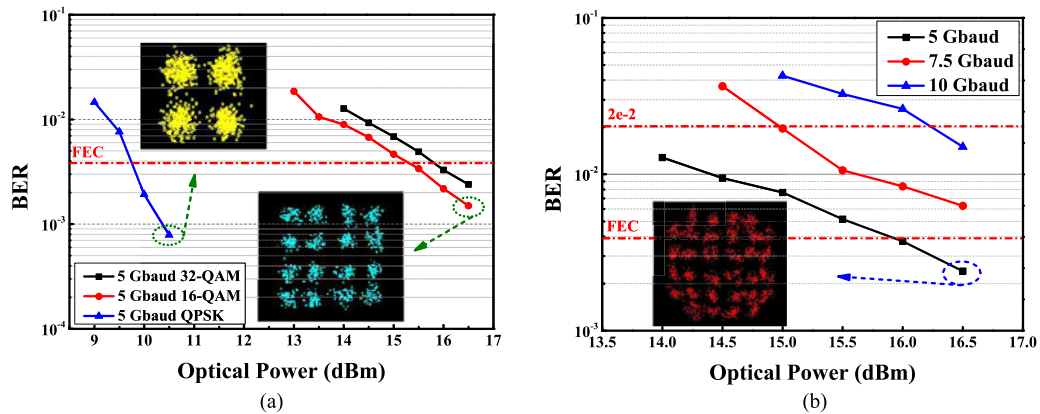


Fig. 8. (a) Measured BER performance for 5 GBd QPSK, 16-QAM, and 32-QAM signals. (b) Measured BER performance for 5, 7.5, and 10 GBd 32-QAM signals.

With regard to the 5 G baud rate, the BER performance for QPSK, 16-QAM, and 32-QAM signals can be seen in Fig. 8(a). A QPSK constellation corresponding to the BER of $7.8\text{e-}4$ and a 16-QAM constellation corresponding to the BER of $1.5\text{e-}3$ are also exhibited. We can observe that the BER performance of all modulation formats can reach below the HD-FEC threshold of $3.8\text{e-}3$ with 7% overhead, and the highest capacity reaches 25 Gb/s. The power penalty between QPSK and 16-QAM is around 6 dB, which is much larger than the 0.5 dB penalty between 16-QAM and 32-QAM. Here such a large penalty can be explained by the limitation of signal processing capability of Keysight DSOZ634A Infiniium, where the processing level of the multi-amplitude signal is much worse than that of single-amplitude signal. Therefore, the processing result for QPSK signal is much better than those for 16-QAM and 32-QAM signals, which are extremely similar. In terms of the 32-QAM signal, in order to explore higher bit rate, we have tried to modulate 7.5 and 10 GBd signals in the experiment. The comparison of BER measurement for 5, 7.5 and 10 GBd, is also shown in Fig. 8(b), where displayed a constellation corresponding to the BER of $2.4\text{e-}3$ with 5 GBd 32-QAM.

Compared to the conventional THz generation by photo-mixing two optical wavelengths from free running lasers [18], [21], the THz carriers in this paper are generated by photo-mixing two coherent optical tones from an optical frequency comb, which would significantly improve the stability and purity of THz carriers and, hence, reduces the complexity and processing time of digital signal processing (DSP). Therefore, this scheme will be of interest for future wireless communication systems which require quick response.

5. Conclusions

We have experimentally demonstrated a THz photonic wireless transmission system at 400 GHz band with OOK, QPSK, 16-QAM, and 32-QAM modulation formats, based on photonic generation of highly pure THz carrier. The phase noise of the 400 GHz signal is theoretically analyzed and experimentally examined by varying the beating path-length difference between the optical LO and the modulation line. The experimental results indicate the purity of generated THz beat-notes is severely influenced by the beating path-length difference and, consequently, significantly affects THz wireless communication performance. Highly pure THz beat-notes can be obtained by compensating the beating path-length difference and, hence, enables the exploration of higher order modulation formats, providing a path to scale THz wireless communication to higher data rates.

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